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On the Feasibility of Charged Particle-Beam Preheat for MagLIF

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Abstract

It is shown that charged particle beams are not promising as an approach to preheating the fuel in a MagLIF implosion.

Introduction

MagLIF requires fuel preheating before the implosion due to the relative slow implosion velocities, as compared to traditional inertial confinement fusion (ICF). The present approach is to use lasers to provide the necessary preheat energy. However, laser interactions with material are complicated by refraction and laser plasma instabilities (LPI). Consequently it is frequently asked if there is a practical alternative. In particular, "*could charged-particle beams be used for this task*"? Charged particle beams have also been studied as a possible means of driving ICF targets. Results from this research are used to show that charged particle beams are not a promising approach to preheating MagLIF fuel.

MagLIF Preheat Requirements

The required MagLIF preheat energies are modest (2-6 kJ) for implosions driven by the present Z machine, but increase with drive current. 2D Lasnex simulations indicate that 30 kJ would be optimal for a gas burning MagLIF target driven by Z300 at a peak current of about 48 MA. Similar simulations also indicate that about 40 kJ will be needed for high-yield ice burning MagLIF liners driven with even higher current.

This preheat energy must be delivered in an appropriate time window and focussed to a small enough radius to fit through an entrance hole. The MagLIF implosion phase takes about 50 - 60 ns so the preheat energy should be delivered in a time not longer than about 30 ns. Thus the preheat power must be about 1 TW or greater. Since the entrance hole allows fuel to escape during the implosion it is desirable to keep this as small as possible. Furthermore, simulations indicate that the performance is enhanced when the heated region has a radius less than 0.5

times the inner radius of the liner, which is typically less than 4 mm. Consequently we assume that the preheat energy must be delivered within a radius of less than 2 mm. Furthermore the energy must be deposited within the 1 cm length of a typical MagLIF liner.

Electron Beams

Electron beams were looked at as a possible ICF driver due to the high beam intensities that had been achieve (~30 TW/cm^2) with MV beams. However, it was quickly realized that the stopping range was much too long. In fact it was for this reason that magnetized fuel was used in the so-called "Phi Targets". It is straightforward to show that low stopping powers make the use of electron beams impractical for preheating MagLIF fuel. The optimal fuel density for a Z300 MagLIF target is about 4.5 mg/cc. At this density, a 45 keV electron will have the correct range to stop in 1 cm ["Stopping Powers for Electrons and Positrons", International Commission on Radiation Units and Measurements, Report 37 (1984)]. Thus to deliver 1 TW of electron beam power we will need a beam current of 22 MA. The cyclotron radius of a 45 keV electron in a 10 Tesla field is about 0.07 mm so the electrons will be effectively tied to the field lines. This suggests that an electron diode could be placed in the fringe field region of the applied Bz with a radius comparable to the radius of the field coils, i.e. about 5 cm. The current density produced by a space-charge limited diode is given by the Child-Langmuir law.

$$J = \frac{4\varepsilon_0}{9}\left(\frac{2eZ}{m}\right)^{1/2}\frac{V^{3/2}}{d^2} , \quad (1)$$

where d is the diode gap and V is the diode voltage. Assuming a diode voltage V=45 kV, we find d/r ~ 1.8x10^{-3}. Even if a 10 cm radius could be used the diode gap would be only 0.18 mm, which is impractically small.

Ion Beams

A proton with an energy of approximately 800 keV would stop in about 1 cm in DT at 4.5 mg/cc [J.F. Ziegler, "Handbook of Stopping Cross-sections for Energetic Ions in All Elements", Vol. 5 Pergamon Press (1980)]. Ion beams with similar energies were produced and studied with the so called "Applied-B" ion diode on Proto-II here at Sandia [D.J. Johnson et al, J. Applied Physics 54, 2230 (1983)]. Current densities of 5-6 kA/cm^2 were achieved with diode voltages of about 1.5 MV. The effective gap according to eq. 1 was about 1 mm even though the actual physical gap was 5 mm. This was due to the space-charge of electrons, which formed a virtual cathode. Despite these high current densities, these diodes never achieved intensities high enough to be useful for driving fusion implosions. The focussing was limited by a spread in the ion directions of about 15 mrad. An ion diode with a cone angle of 0.2 mrad (equivalent to an F number of 5) would have to be placed within 7 cm from the end of a MagLIF target to keep the beam focus

within a 2 mm radius. The anode area would then be only about 6 cm^2, which implies a current of ~ 36 kA and a beam power of 0.03 TW. This is much too small to effectively preheat the gas in MagLIF.

In principle higher deposition rates could be possible with heavier ions. Lithium was studied within the light ion program. The highest intensity achieved using PBFA-II (later converted to Z) was 1.8 TW/cm [D.J. Johnson et al., Laser and Particle Beams 16, 185 (1998)]. This is more than a factor of 4 too low to provide 1 TW hitting a radius of 0.2 cm, which is needed to preheat the fuel of high yield MagLIF targets.

Conclusion

These simple arguments don't prove that it would be impossible to preheat MagLIF fuel, but at the very least it would require a separate research program.

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